US005599223A

United States Patent [19]

Mains Jr.

[11] Patent Number: 5,599,223

[45] Date of Patent: *Feb. 4, 1997

[54] METHOD FOR MATERIAL REMOVAL

[76] Inventor: **Gilbert L. Mains Jr.**, 2642 Joelle Dr., Toledo, Ohio 43617

[*] Notice: The term of this patent shall not extend beyond the expiration date of Pat. No. 5,222,332.

[21] Appl. No.: **265,430**

[22] Filed: **Jun. 24, 1994**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 986,379, Dec. 7, 1992, Pat. No. 5,341,608, which is a continuation of Ser. No. 684,979, Apr. 10, 1991, Pat. No. 5,222,332.

[51] **Int. Cl.**^{6} **B24C 1/00**

[52] **U.S. Cl.** **451/39**; 451/40; 451/53; 83/53; 83/177; 134/24

[58] **Field of Search** 83/16, 53, 169, 83/177; 134/6, 7, 8, 24; 451/39, 40, 53

[56] **References Cited**

U.S. PATENT DOCUMENTS

2,985,050	5/1961	Schwacha	83/53
3,508,621	4/1970	Gaylord et al.	451/39 X
3,676,963	7/1972	Rice et al.	451/39
3,712,306	1/1973	Bryne	606/22
3,746,256	7/1973	Hall et al.	239/101
3,900,975	8/1975	Lightstone et al.	451/53
3,979,981	9/1976	Lightstone et al.	83/15
4,262,567	4/1981	Bettin	83/171
4,389,820	6/1983	Fong et al.	451/75
4,447,952	5/1984	Elkins	30/361
4,508,577	4/1985	Conn et al.	134/24 X
4,594,924	6/1986	Windisch	83/177
4,658,683	4/1987	Phillips	451/40 X
4,686,877	8/1987	Jaritz et al.	83/177
4,693,153	9/1987	Wainwright et al.	83/53
4,723,387	2/1988	Krasnoff	451/75
4,806,171	2/1989	Whitlock et al.	134/7
4,829,859	5/1989	Yankoff	82/1.11
4,918,941	4/1990	Hagler	62/320
5,001,873	3/1991	Rufin	451/39
5,009,240	4/1991	Levi	134/7
5,018,667	5/1991	Lloyd	239/132.5
5,025,597	6/1991	Tada et al.	451/75
5,097,731	3/1992	Vives et al.	83/53
5,165,602	11/1992	Arnout et al.	239/8
5,222,332	6/1993	Mains, Jr.	451/39
5,341,608	8/1994	Mains, Jr.	451/39

FOREIGN PATENT DOCUMENTS

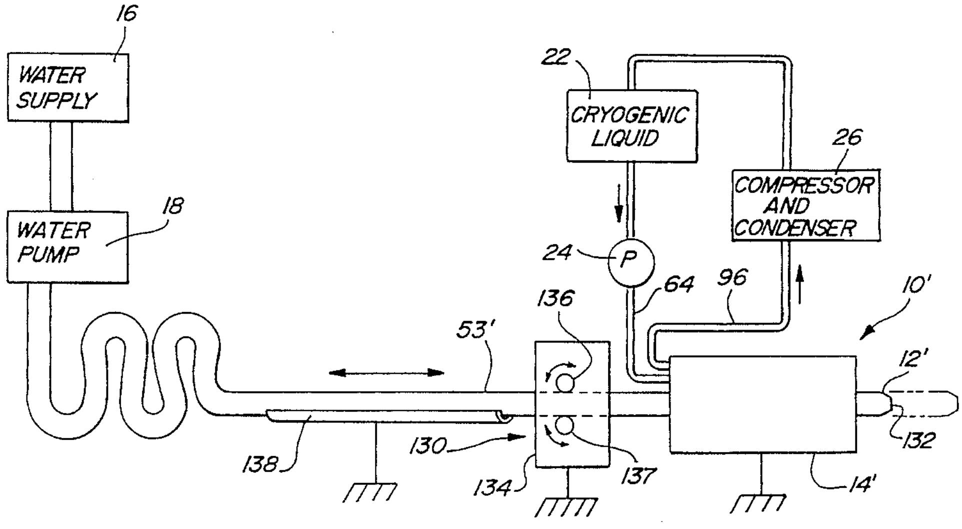
2475425	8/1981	France .
2042399	9/1980	United Kingdom .

Primary Examiner—Rinaldi I. Rada
Assistant Examiner—Raymond D. Woods
Attorney, Agent, or Firm—Reising, Ethington, Barnard & Perry

[57] ABSTRACT

A method and apparatus that allows the removal of solid material from a workpiece utilizes a high velocity stream of ice which is caused to impinge on the workpiece. A working liquid, such as water, is supplied at high pressure to a discharge nozzle with an orifice for forming the needle-like stream. The water is cooled before it reaches the nozzle to a temperature below its freezing point so that at least some of the stream is transformed to ice. Optionally, the stream is cooled after it is emitted from the orifice by flowing an envelope of cryogenic gas around the emitted stream. The apparatus includes an inner conduit that carries the working liquid through a cutting tool where the liquid is at least partially solidified by an evaporator that utilizes a cryogenic fluid to cool the working liquid. In a second embodiment, the inner conduit can be moved longitudinally through the cutting tool from a position in which the orifice is proximate the cutting tool to a position in which the orifice is located remotely of the cutting tool. This allows the inner conduit to be indexed into the workpiece to make deep cuts without having to make a wide cut to accept the cutting tool.

12 Claims, 6 Drawing Sheets



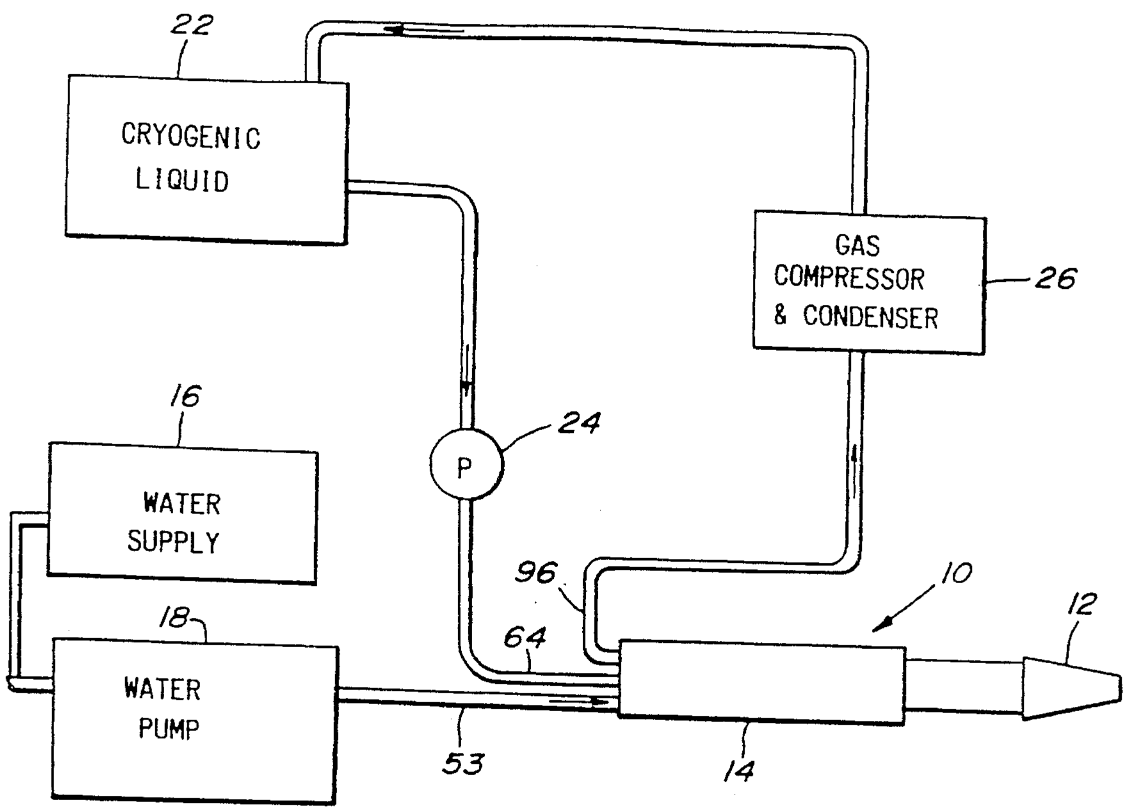

22
CRYOGENIC LIQUID
GAS COMPRESSOR & CONDENSER
26
16
WATER SUPPLY
24
P
96
10
12
18
WATER PUMP
64
53
14

Fig-1

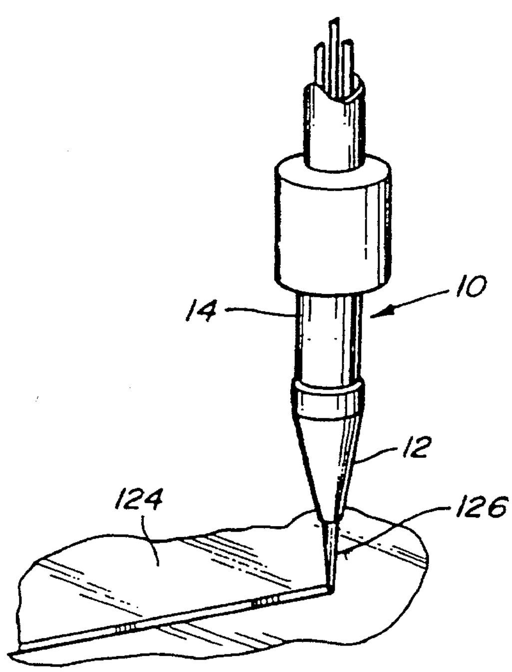
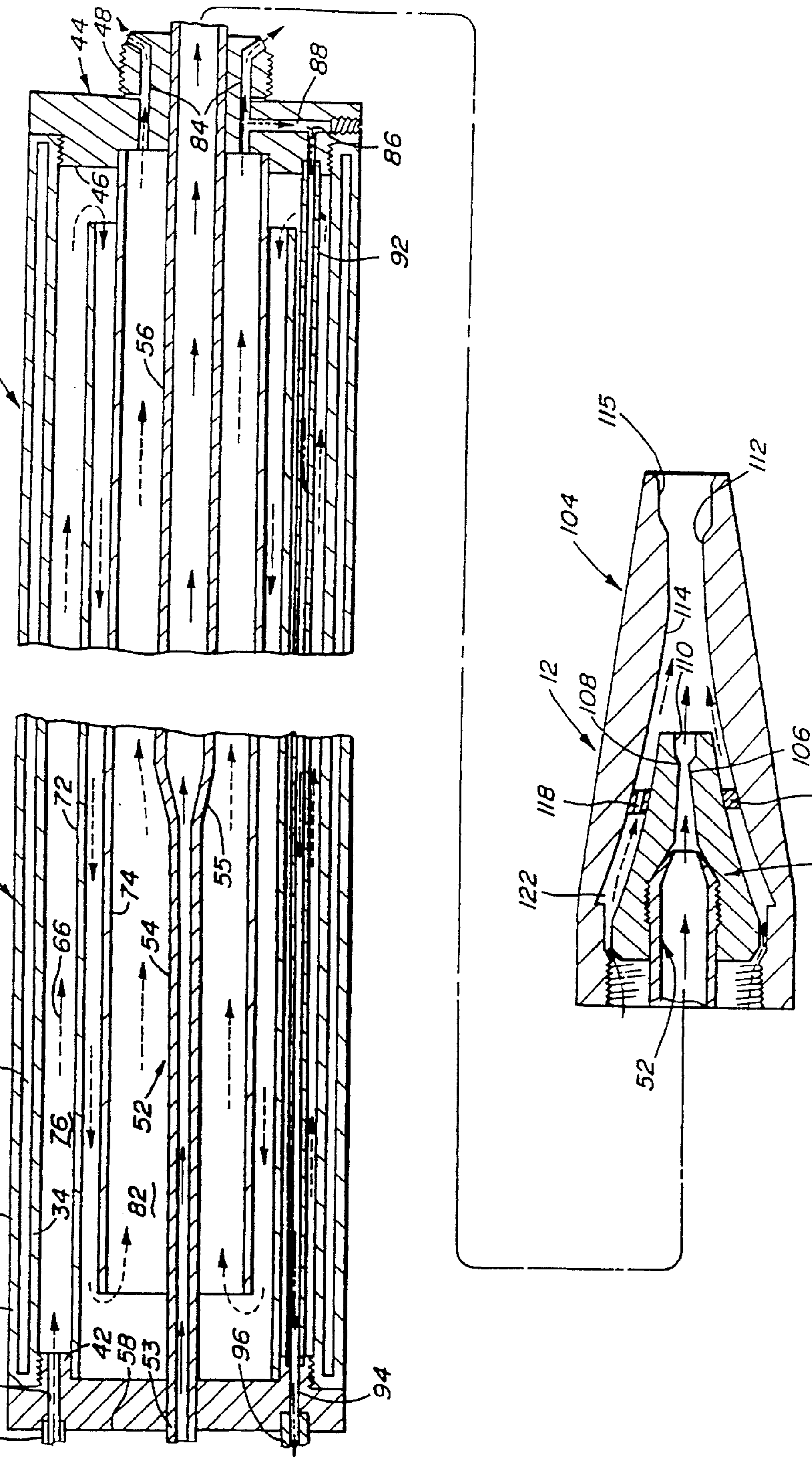

10
14
12
124
126

Fig-2



10
14
12
104
102
115
112
114
110
108
106
116
118
122
52
44
48
84
88
86
46
92
56
72
74
66
54
55
36
76
32
34
34'
82
62
42
58
53
96
94
64

Fig-3

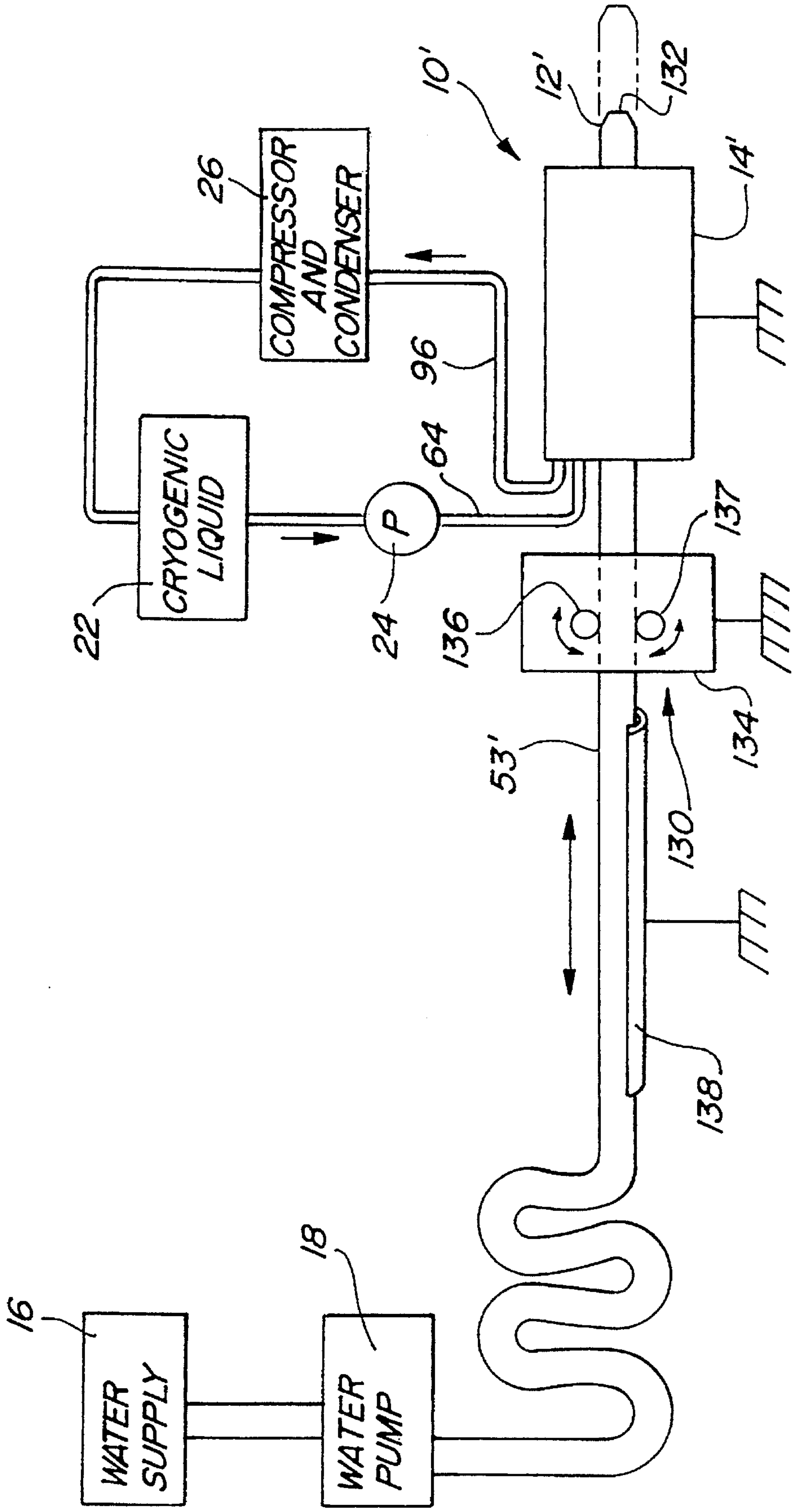

10'
12'
132
14'
26
COMPRESSOR AND CONDENSER
96
64
22
CRYOGENIC LIQUID
P
24
136
137
134
53'
130
138
16
WATER SUPPLY
18
WATER PUMP

Fig - 4

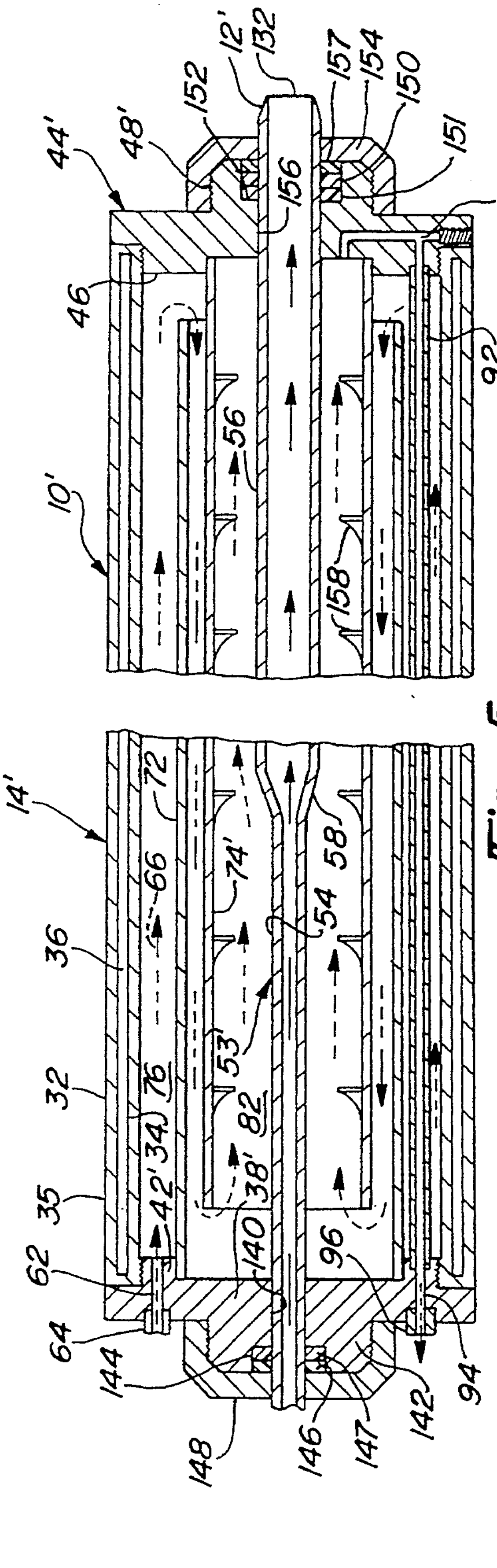


Fig - 5

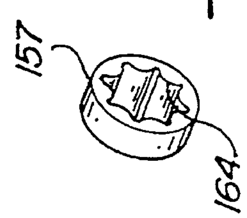


Fig - 7

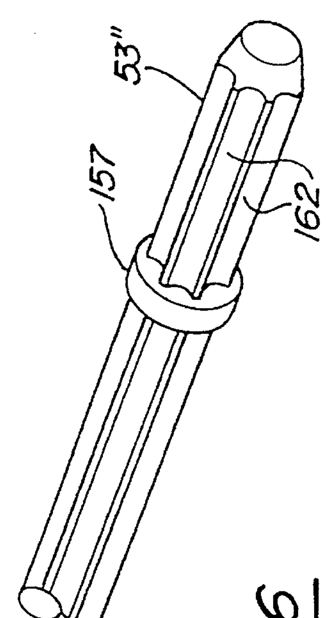


Fig - 6

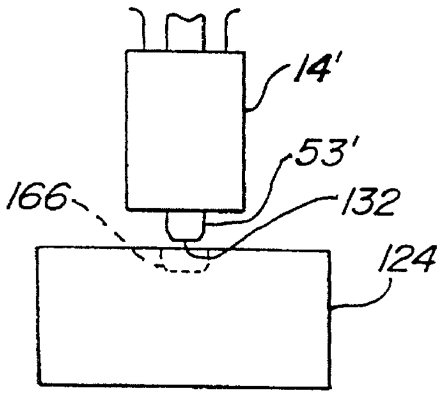


Fig - 8A

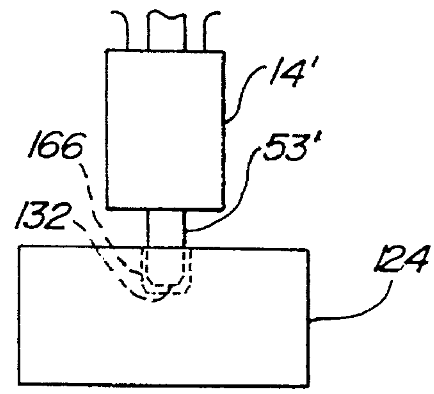


Fig - 8B

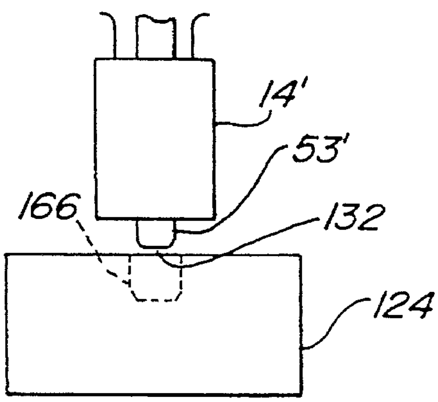


Fig - 8C

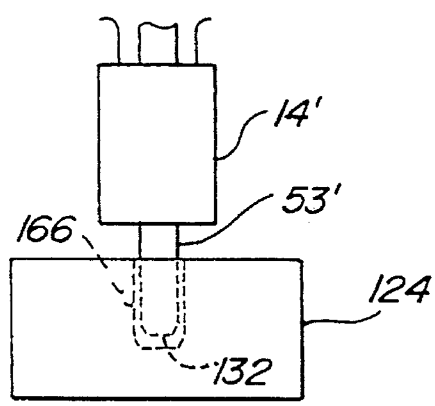
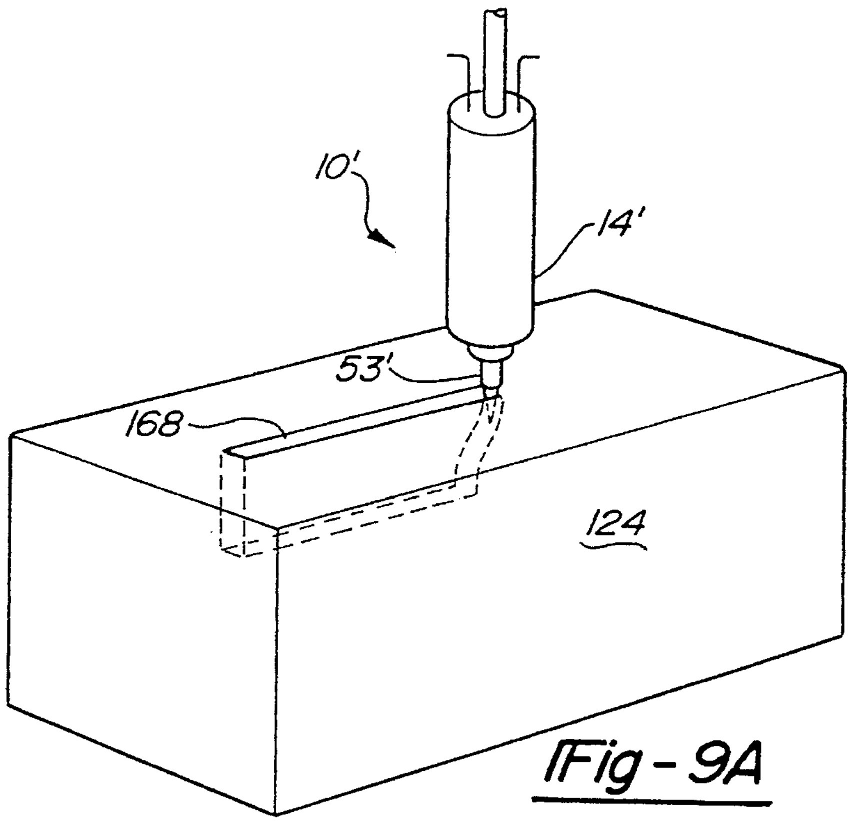
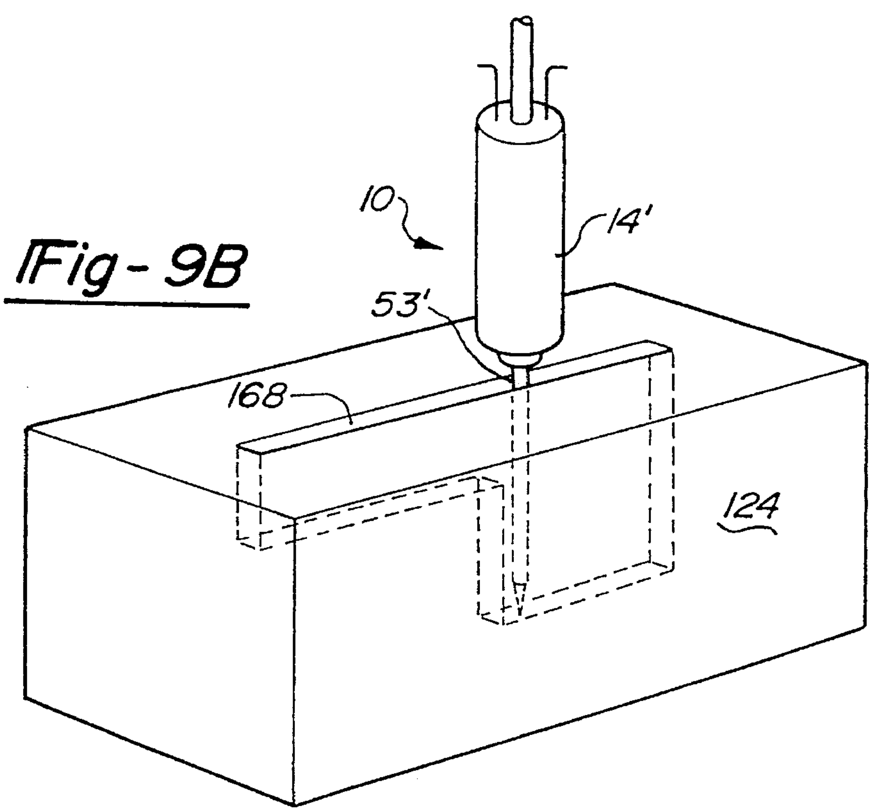


Fig - 8D



IFig - 9A



IFig - 9B

METHOD FOR MATERIAL REMOVAL

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of U.S. Ser. No. 07,986,379, filed Dec. 7, 1992, now U.S. Pat. No. 5,341,608, which is a continuation of U.S. Ser. No. 07/684,979, filed Apr. 10, 1991, now U.S. Pat. No. 5,222,332, issued Jun. 29, 1993.

FIELD OF THE INVENTION

This invention relates to a method and apparatus for removal of material from solid bodies; more particularly, it relates to material removal by the use of a high velocity jet formed from a liquid.

BACKGROUND OF THE INVENTION

There are many industrial operations which require processing of solid workpieces by material removal to cut, shape or clean the workpiece. It is already known, and commonly used in industry, to utilize high pressure, high velocity liquid jets for such material removal operations. These known methods and apparatus have achieved a high state of development but still leave much to be desired in respect to efficiency of material removal and residual effects on the workpiece and on the work site.

In the prior art, solid workpieces of hard material are cut by use of high velocity liquid jets which effect the cut by material removal in particulate form from the kerf. In some applications, an abrasive material is added to the jet stream to enhance the cutting action. Water and other liquids have been proposed for use in the formation of the jet stream. This cutting technique has been proposed for application to cutting of metal workpieces including exotic metals which are extremely hard. It has also been proposed for use in cutting composite materials, concrete and stone.

It has been a common practice to clean the surfaces by the use of sand blasting and the use of water blasting with entrained abrasive particles, for example in the removal of unwanted deposits on the exterior walls of buildings of brick and stone. This method of material removal typically leaves a very large amount of residue of the working fluid.

The prior art methods and apparatus for material removal as discussed above, are inefficient, produce a low rate of material removal and leave an unduly large amount of residue and waste at the work site. There is a need to overcome such disadvantages in a wide variety of industrial applications. A particular application, for example, is stone cutting in quarrying operations. In such operations, such as the mining of granite blocks, the cutting operation has to be performed in a relatively confined area wherein the cutting tool has to be manually supervised and controlled or sometimes manually manipulated. In such an operation, huge blocks of granite weighing many tons, for example, are cut in rectangular form from a monolith of great extent. It is desirable to sever the block with a narrow kerf and thereby minimize the amount of material removal required. It is also desirable to minimize the contamination of the air in the work area and to leave only a minimum amount of harmless residue.

The following patents relate to methods and apparatus for material removal by use of the high velocity jet stream of liquid or other material: U.S. Pat. Nos. 2,985,050 Schwacha, issued May 23, 1961; 3,746,256 Hall et al, issued Jul. 17,

1973; 4,594,924 Windisch, issued Jun. 17, 1986; 4,686,877 Jaritz et al, issued Aug. 18, 1987; 4,693,153 Wainwright et al, issued Sep. 15, 1987; and 4,723,387 Krasnoff, issued Feb. 9, 1988.

It is known in the prior art to use carbon dioxide in solid phase for use in cleaning a workpiece. In this prior art solid pellets of carbon dioxide are formed on the surface of a drum which is rotated at high speed to throw the pellets by centrifugal force against a workpiece for cleaning or other purposes.

The following patents relate to the use of cryogenic fluids in connection with cutting apparatus or methods. The Lightstone et al U.S. Pat. No. 3,979,981, issued Sep. 14, 1976 discloses a method for shearing metal in which the metal is cooled to a cryogenic temperature and using shearing operations such as slitting, punching, and blanking. The Lightstone et al U.S. Pat. No. 3,900,975, issued Aug. 26, 1975 discloses a process for abrasively grinding copper in which the copper workpiece is cooled to a cryogenic temperature. The Elkins U.S. Pat. No. 4,447,952, issued May 15, 1984 describes an underwater cutting or penetrating device which uses a source of liquid nitrogen for cooling a workpiece before impact by an explosively driven member. The Bryne U.S. Pat. No. 3,712,306, issued Jan. 23, 1973 discloses a cryosurgical instrument which has an open ended chamber pressed into contact with tissue. A stream of liquified nitrogen impinges directly on the tissue which is to be necrotized by freezing. The Bettin U.S. Pat. No. 4,262,567, issued Apr. 21, 1981 and the Hagler U.S. Pat. No. 4,918,941, issued Apr. 24, 1990 disclose the use of cryogenic fluids for cooling microtomes.

A general object of this invention is to provide an improved method and apparatus for material removal by a high velocity stream impinging on the workpiece and to overcome certain disadvantages of the prior art.

SUMMARY OF THE INVENTION

In accordance with this invention, method and apparatus are provided for material removal from a solid workpiece using a high velocity jet stream formed from a working liquid and containing solid particles but which leaves no solid residue. This is accomplished by producing a high speed jet stream containing needles or particles of ice.

In accordance with this invention, solid material is removed from a workpiece by supplying a pressurized working liquid to a discharge nozzle having an orifice for emitting a needle-like stream at high velocity. The working liquid is cooled before it reaches the nozzle to a temperature below its freezing point whereby at least some of the stream is in a solid phase state. The stream issuing from the orifice is caused to impinge on the workpiece to dislodge solid material therefrom. Optionally, the stream may be cooled after it is emitted from the orifice to maintain it below its freezing point between the orifice and the workpiece. Preferably, the pressurized working liquid is water which is cooled by a cryogenic fluid.

In accordance with another aspect of the invention, deep holes and cuts can be bored using an embodiment of the invention in which the working material flows through a conduit that can be indexed into the hole (or cut) in the workpiece. The conduit is part of a charge forming barrel that includes an evaporator that is thermally coupled to the conduit to remove heat from the working material flowing through the conduit. The conduit is normally maintained in a retracted position in which the orifice of the conduit is proximate the evaporator. This minimizes the length of the conduit extending between the exit point of the evaporator and the orifice and therefore aids in minimizing the temperature of the working material at the orifice.

Initially, the orifice is held near the surface of the workpiece as boring of the workpiece begins. Once a hole has been bored to a depth such that the cutting action is diminished, the conduit can be indexed through the evaporator and into the hole so as to bring the orifice near the bottom of the hole in the workpiece. In this way, deep cuts can be made without having to make a hole that is wide enough to accept the evaporator. In the event that the temperature of the working material emitted from the orifice rises as a result of the orifice being indexed into the hole and away from the evaporator, the conduit can be retracted until the orifice is again proximate the evaporator and then held there until the temperature of the working material lowers to the point that the stream includes a sufficient amount of solidified material to provide the desired cutting action. Thereafter, the conduit can be extended into the hole for further cutting.

A complete understanding of this invention will be obtained from the detailed description that follows taken with the accompanying drawings.

DESCRIPTION OF THE DRAWINGS

FIG. **1** is a diagram of a first embodiment of the invention;

FIG. **2** shows the apparatus of FIG. **1** in relation to a workpiece;

FIG. **3** shows certain details of construction of the apparatus of FIG. **1**;

FIG. **4** is a diagram of a second embodiment of the invention;

FIG. **5** shows greater detail of the cutting tool shown in FIG. **4**;

FIG. **6** is a perspective view of an indexable, fluted conduit and seal back-up ring that can be used with the second embodiment;

FIG. **7** is an end view of the seal back-up ring of FIG. **6**;

FIGS. **8A–8D** together show a process for boring a hole using the apparatus of FIGS. **4** and **5**; and

FIGS. **9A** and **9B** together show a process for boring a slot using the apparatus of FIGS. **4** and **5**.

BEST MODE FOR CARRYING OUT THE INVENTION

Referring now to the drawings, there is shown illustrative embodiments of the invention in a material removing apparatus which is especially adapted for cutting of stone and concrete. It will be appreciated, as the description proceeds, that the invention may be embodied in different forms and may be utilized in a wide variety of applications.

A first embodiment of the material removing apparatus of this invention is illustrated in FIG. **1** in diagrammatical form. It comprises, in general, a cutting tool **10** including a nozzle **12** and a charge forming barrel **14**. The cutting tool **10** is supplied with a working liquid, specifically water, from a water supply source **16** through a high pressure pump **18**. For the purpose of freezing the water as it is emitted from the nozzle **12**, the cryogenic liquid supply source **22** is connected through a pump **24** to the tool **10**. For the purpose of conserving the cryogenic material, at least a portion of the cryogenic gas which flows through the charge forming

barrel **14** is returned through a gas compressor and condenser **26** to the supply source **22**.

The cutting tool **10** will be described in greater detail with reference to FIG. **3**. The charge forming barrel **14** comprises an insulating cylindrical sleeve **32** of double wall construction. The inner and outer walls **34** and **35** are radially spaced and hermetically joined at the ends to form enclosed annular chamber **36** which is evacuated to provide thermal insulation. A rear end cap **38**, suitably circular, is provided with an annular boss **42** which threadedly engages the cylindrical sleeve **32** and forms a gas-tight closure therewith. Similarly, a front end cap **44** is provided with an annular boss **46** which is threadedly engaged with the cylindrical sleeve **32** in gas-tight sealing engagement therewith. The front end cap **44** is provided with a unitary nozzle fitting **48** to receive the nozzle **12** which will be described subsequently.

The charge forming barrel **14** includes a centrally disposed water conduit **52** extending axially through the rear end cap **38**, the cylindrical sleeve **32** and the nozzle fitting **48**. The inlet end of the conduit **52** is connected by a water supply conduit **53** to the pump **18**. The water conduit **52** has a section **54** of relatively small internal diameter and a section **56** of relatively large internal diameter, the sections being joined by an expansion throat **58**. As will be described, water is flowed through the water conduit **52** at very high pressure from the pump **18**. A flow regulating valve may be connected in the supply conduit **53** to permit adjustment of flow to a desired value.

The water in the conduit **52** is refrigerated by a flow of cryogenic fluid in the charge forming barrel **14** to transform the water from liquid phase to solid phase in the form of ice crystals as will be described. Refrigeration of the water in the conduit **52** is provided by a cryogenic fluid evaporator in heat exchange relation with the conduit in the charge forming barrel **14**. The evaporator comprises an expansion chamber with a retroverted flow path for the cryogenic fluid. The flow path enters the charge forming barrel **14** through a passage **62** which is connected by a conduit **64** to the cryogenic liquid pump **24**. The flow path for the cryogenic fluid is indicated by the dashed-line arrows **66**. The path is defined by a pair of coaxial sleeves **72** and **74**, the former being secured in the annular boss **42** of the rear end cap **38** and the latter being secured in the annular boss **46** of the front end cap **44**. Thus, the gas is constrained to flow in an outer annular passage **76** between the insulating cylindrical sleeve **32** and the sleeve **72** in the forward direction and then in the reverse direction through an intermediate annular passage **78** between the sleeves **72** and **74**. In a final pass, the cryogenic fluid flows in the inner annular passage **82** between the sleeve **74** and the water conduit **52**. In order to supply the cryogenic fluid to the nozzle **12**, the nozzle fitting **48** is provided with plural axial passages **84** extending from the passage **82** to the nozzle **12**, which will be described subsequently.

For the purpose of conserving the cryogenic fluid which is not supplied to the nozzle **12**, a return flow path, indicated by the interrupted line arrows **86**, is provided in the charge forming barrel **14**. This return flow path includes a passage **88** in the front end cap **44** which intersects one of the passages **84**. It also includes a tube **92** extending from the passage **88** throughout the length of the barrel **14** to a passage **94** in the rear end cap **38**. A conduit **96** connects the passage **94** in the rear end cap **38** to the gas compressor and condenser **26**.

The nozzle **12** comprises an inner nozzle member **102** and a coaxial outer nozzle member **104**. The inner nozzle member is mounted on the forward end of the water conduit **52** by a threaded connection. It is provided with a conical nose and an axially extending venturi passage **106** having a throat **108** of reduced diameter leading to an orifice **110** of somewhat larger diameter. An outer nozzle member **104** is provided with a tapered bore **114**, somewhat conical in shape. The bore **114** has a minimum diameter at an orifice **112** and has a larger diameter at mouth **115**. The bore **114** terminates at its rear end in a cylindrical threaded opening which is threadedly engaged with the nozzle fitting **48**. An annular orifice plate **116** is disposed over the conical nose of the inner nozzle member **102** in conforming engagement therewith and has a conforming engagement at its outer periphery with the tapered wall of the bore **114** in the outer nozzle member **104**. The orifice plate **116** is provided with a plurality, suitably six, orifices **118**. An annular passage **122** is defined between the inner wall of the outer nozzle **104** and the outer wall of the inner nozzle **102** and extends from the axial passages **84** in the fitting **48** to the orifices **118** in the orifice plate **116** to provide for a regulated flow of cryogenic fluid therethrough.

In operation, as depicted in FIG. **2**, the cutting tool **10** is adapted to remove material from a stone workpiece **124** by emitting a needle-like stream **126** of ice or particles of ice which impinges at high velocity against the workpiece. Water is delivered by the water pump **18** at very high pressure through the supply conduit **53** to the water conduit **52** of the charge forming barrel **14**. There is a pressure drop and reduction in flow rate at the expansion throat **58** and through the conduit section **56** between the throat **58** and the inner nozzle **102**. The cryogenic liquid from the source **22** is supplied by the pump **24** through the conduit **64** to the inlet passage **62** in the charge forming barrel **14**. The annular passages **76**, **78** and **82**, which are of greatly increased cross-sectional area compared with the inlet passage **62**, serve as an evaporator in which the cryogenic liquid vaporizes and flows through the annular passages in gaseous form. This produces a refrigerating effect on the water conduit **52** and the high pressure water stream therein is frozen into a column of ice. The stream of water under high pressure in the small diameter section **54** of the conduit **52** is in a supercooled state. In this section **54**, the temperature is below the freezing point of water but the water therein remains in the liquid state due to the high pressure. At the expansion throat **58** the pressure on the water decreases and sufficient expansion is permitted to allow transformation to the solid state in the form of a column of ice. The column of ice is forced by the high pressure water behind it through the venturi passage **106** in the inner nozzle member **102** and is emitted therefrom. There is a needle-like stream moving at high velocity through the orifice **112** in the outer nozzle member **104**. A portion of the cryogenic gas in the charge forming barrel **14**, pressurized by the expansion therein, is forced through the passages **84** to the nozzle fitting **48** and into the annular passage **122** of the nozzle **12**. The cryogenic gas flows through the orifices **118** in the orifice plate **116** and forms an envelope or sheath of cryogenic gas around the needle-like stream of ice which is projected at high velocity through the orifice **112**. Thus, the gaseous sheath, which is below the freezing point of water, maintains the needle-like stream of ice in the solid state as it impinges upon the workpiece surface.

An example of a design of the cutting tool **10** is as follows. The tool is designed to use liquid nitrogen as the cryogenic liquid with water as the working liquid. The water pump **18** has the capacity to deliver water at 20,000 PSI through the supply conduit **53** at a flow rate of twelve gallons per minute to the inlet of the water conduit **52** on the charge forming barrel **14**. The cryogenic liquid pump **24** has the capacity to deliver cryogenic liquid nitrogen through the conduit **64** at a pressure of 350 PSI to the inlet passage **62** in the charge forming barrel **14**. Selected dimensions of the charge forming barrel and nozzle are as follows:

Charge forming barrel **14**:
Length=20 ft.,
Diameter=2 in.;

Inlet passage **62**:
Inside Diameter (I.D.)=3/16 in.;

Section **54** of water conduit **52**:
Length=5 ft.,
I.D.=1/16 in.;

Section **56** of water conduit **52**:
Length=15 ft.,
I.D.=1/8 in.

Nozzle fitting **48**, six passages **84**:
Diameter=1/16 in.

Orifice plate **116**, six orifices **118**:
Diameter=0.0052 in.;

Nozzle member **104**:
Orifice **112**, diameter=1/4 in.,
Mouth **115**, diameter=3/16 in.;

Nozzle member **102**:
Venturi throat **108**, Diameter=0.052 in.,
Orifice **110**, Diameter=0.062 in.

A second embodiment of the apparatus of the invention will now be described in connection with FIGS. **4**–**9**, wherein elements in common with the embodiment of FIGS. **1**–**3** are denoted with like numerals and wherein modified elements of the embodiment of FIGS. **1**–**3** are denoted with primed numerals.

As shown in FIG. **4**, cutting tool **10'** comprises a nozzle **12'** and a charge forming barrel **14'**. Cutting tool **10'** is supplied with a liquid working material such as water via conduit **53'**. The constructions and functions of water supply **16**, high pressure pump **18**, cryogenic liquid supply source **22**, pump **24**, and gas compressor and condenser **26** are the same described in connection with the first embodiment and the discussion will therefore not be repeated. The apparatus includes a pneumatically or hydraulically actuated drive **130** that indexes conduit **53'** through charge forming barrel **14'**. The conduit is shown in FIG. **4** in its retracted position in which orifice **132** of nozzle **12'** is proximate charge forming barrel **14'**.

Drive **130** is shown diagrammatically in FIG. **4** as a housing **134** and a pair of drive rollers **136** and **137** that are rotated together in opposite directions to either extend or retract conduit **53'**. Various constructions of drive **130** will be apparent to those skilled in the art. Drive **130** can be operated to index conduit **53'** for a limited distance from its retracted position to an extended position selectable by the user. Indexing of conduit **53'** moves it through barrel **14'** which is fixed in position with respect to drive **130**. Indexing of conduit **53'** also moves it along a track **138** that supports conduit **53'**. An exemplary extended position of conduit **53'** is indicated by broken lines in FIG. **4**.

Referring now to FIG. **5**, cutting tool **10'** has a construction similar to that of cutting tool **10**, except that nozzles **102** and **104** have been eliminated and the ends of barrel **14'** include seals to permit longitudinal movement of conduit **53'** through barrel **14'** without any loss of cryogenic fluid. In particular, nozzles **102** and **104** of FIG. **3** have been eliminated in this embodiment in order to minimize the diameter of nozzle **12'**. This enables the diameter of the bored hole to be kept to a minimum to thereby reduce the amount of waste produced. This reduction of waste not only minimizes the amount of debris produced by the material removal operation, but is particularly useful in quarrying where it is desirable to maximize the yield from any particular block of stone. Moreover, by cutting less material, the operation can be performed faster and with less effort.

End cap **38'** includes an aperture **140** through which conduit **53'** extends. End cap **38'** includes a threaded extension **142** that has a recess **144** that receives a pair of seals **146, 147**. Seals **146** and **147** prevent loss of cryogenic fluid from passage **82** between aperture **140** and conduit **53'**. Seals **146** and **147** can each be a V-ring packing or other suitable seal made from a composite material capable of providing a fluid-tight seal at the temperatures experienced at end cap **38'** due to the presence of the cryogenic fluid within barrel **14'**. A cap nut **148** is threaded over extension **142** to retain seals **146** and **147** within recess **144**. End cap **44'** has a similar construction, with seals **150** and **151** being retained within a recess **152** by a cap nut **154** to seal at aperture **156** of end cap **44'**. End cap **44'** includes a metal seal back-up ring **157**, the construction and function of which will be described below .

If cutting tool **10'** includes sections **54** and **56** of conduit **53'**, then the maximum distance by which conduit **53'** can be indexed out through end cap **44'** must be limited so as to prevent expansion throat **58** from exiting through aperture **156** in end cap **44'**. Otherwise, the seal provided by seals **150** and **151** would be lost due to the smaller outer diameter of section **54** of conduit **53'**.

If desired, sleeve **74'** can include a plurality of fins **158** on its inner surface to swirl the cryogenic fluid as it moves through passage **82** to improve the cooling of the working material within conduit **53'**. Fins **158** could be added to the inner surface of sleeve **74'** by cutting sleeve **74'** in half lengthwise, welding or otherwise attaching fins **158**, and then welding the two halves of sleeve **74'** back together.

To aid in the removal of waste material from the hole as it is being bored, conduit **53"** shown in FIGS. **6** and **7** can be used in place of conduit **53'**. Conduit **53"** is fluted in its lengthwise direction, as indicated at **162**. Also shown in FIG. **6** is seal back-up ring **157**. Referring again briefly to FIG. **5**, back-up ring **157** holds seals **150** and **151** in place. Flutes **162** end at expansion throat **58** so that no back-up ring is needed at end cap **38'**. As shown in FIGS. **6** and **7**, back-up ring **157** has an inner coutour **164** that conforms to the outer surface of conduit **53"**. This permits conduit **53"** to be indexed through charge forming barrel **14'** with little or no loss of cryogenic fluid through aperture **156**. When conduit **53"** is indexed into a hole being bored, waste material from the workpiece that is generated in the boring process can exit the hole by moving along the space defined by flutes **162** that exists between conduit **53"** and the side wall of the hole. Other equivalent means for permitting the escape of dislodged pieces of the workpiece from the hole will be apparent to those skilled in the art. For example, inner conduit **53"** could instead include a spiral wrap similar to that of an ordinary drill bit.

Referring now to FIGS. **8A–8D**, a method of boring a hole **166** using the apparatus of FIGS. **4** and **5** will be described. Contrary to that shown in FIG. **4**, cutting tool **10'** is shown in FIGS. **8A–8D** as being disposed in a vertical orientation, in which case drive **130** will be located above cutting tool **10'** and an appropriate support structure would be used in place of support track **138** to hold and guide conduit **53'** into drive **130**. It will thus be appreciated that the apparatus of the invention can be used in whatever orientation is required for a particular application.

As shown in FIG. **8A**, initially hole **166** is begun with conduit **53'** being held in its retracted position in which orifice **132** is near the exit point of charge forming barrel **14'**. As hole **166** is bored deeper, conduit **53'** is then indexed into the hole to maintain orifice **132** near the surface of workpiece **124** from which the removal of material is desired (i.e., near the bottom of hole **166**). This is shown in FIG. **8B**. As will be appreciated by those skilled in the art, the boring operation shown in FIG. **8B** can result in the temperature of conduit **53'** proximate orifice **132** becoming heated due to such things as the heat generated by the removal of material from workpiece **124** and heating of conduit **53'** due to friction from the waste material escaping hole **166** along the outer surface of conduit **53'**. This in turn may result in the solid particles formed in conduit **53'** within barrel **14'** melting prior to impinging upon workpiece **124**. Accordingly, the cutting action of cutting tool **10'** will be reduced. When this happens, conduit **53'** can be indexed back to its retracted position, as shown in FIG. **8C**. Conduit **53'** is then held in its retracted position until the nozzle end of conduit **53'** is cooled sufficiently that it can be indexed back out from its retracted position without melting of the solid particles prior to their exit through orifice **132**. Thereafter, conduit **53'** can be reinserted into hole **166** to continue the boring operation, as shown in FIG. **8D**. This process can be repeated as often as needed until hole **166** is bored to the desired depth.

As will be appreciated from the diagrammatic view provided by FIGS. **8A–8D**, the indexing of conduit **53'** into hole **166** enables workpiece **124** to be bored with only a minimal amount of waste being produced. As an example, a typical granite cutting operation uses compressed air and fuel to blast out holes in the granite that are used for the cutting of the slab. For a four by six foot slab of cut granite, four inches is typically lost due to this process. However, by using the indexable conduit method and apparatus of the invention, the holes can be cut with only a one inch loss of material.

Referring now to FIGS. **9A** and **9B**, a method of cutting a slot **168** using the apparatus of FIGS. **4** and **5** will be described. Initially, conduit **53'** is held in its retracted position while cutting tool **10'** is moved along workpiece **124** to make a first cut, as shown in FIG. **9A**. Thereafter, conduit **53'** is indexed into slot **168** near the bottom of the slot and cutting tool **10'** is again moved along workpiece **124** to make a second cut, as shown in FIG. **9B**. This process can be repeated until the desired depth is reached for slot **168**. As discussed in connection with FIG. **8C**, conduit **53'** can be indexed back to its retracted position as necessary to cool the nozzle end of conduit **53'** to a temperature sufficient to prevent melting of all of the solid particles flowing within conduit **53'** prior to their exit through orifice **132**.

It will be understood that the cutting tools **10** and **10'** of this invention may be used with working liquids other than water such as liquids having a suitably high freezing point or mixtures of water and other liquids or water with dissolved chemicals. Also, it will be understood that cryogenic fluids other than liquid nitrogen may be employed such as liquid carbon dioxide.

Although the description of this invention has been given with reference to a particular embodiment, it is not to be construed in a limiting sense. Many variations and modifications will now occur to those skilled in the art. For a definition of the invention reference is made to the appended claims.

What is claimed is:

1. A method of cutting a solid workpiece, comprising the steps of:

(a) forcing a stream of liquid working material through a conduit having an orifice for emitting the working material,

(b) cooling a section of said conduit that extends through a heat exchanger having a cryogenic fluid in heat exchange relationship with said working material to thereby cause solidification of at least some of the working material emitted through said orifice,

(c) impinging said working material on the workpiece to bore a hole that is dimensioned so as to accept said conduit therein, and

(d) extending said conduit out of said heat exchanger and into the hole while maintaining said heat exchange relationship between said cryogenic fluid and said working material, and impinging said working material on the workpiece within the hole.

2. The method of claim **1**, further comprising the steps of:

(e) retracting said conduit out of the hole and back into said heat exchanger, and

(f) repeating steps (b) through (d).

3. The method of claim **2**, further comprising the step of repeating steps (b) through (e) in succession until the hole has a desired depth.

4. The method of claim **1**, wherein:

step (c) further comprises the step of moving said orifice along a path over a surface of the workpiece so as to bore the hole as a slot in the workpiece, and

step (d) further comprises extending said conduit into the slot and moving said orifice along said path while impinging said working material on the workpiece within the slot.

5. The method of claim **1**, further comprising the step of, prior to step (a), forming said conduit such that pieces dislodged from the workpiece that are within the hole can move along said conduit and out of the hole.

6. The method of claim **1**, further comprising the step of cooling a section of said conduit remote from said orifice during step (d) to a temperature sufficient to cause solidification of at least some of said working material to thereby form solid particles that are emitted through said orifice.

7. The method of claim **1**, further comprising the step of using liquid nitrogen as said cryogenic fluid.

8. The method of claim **1**, further comprising the step of using liquid carbon dioxide as said cryogenic fluid.

9. The method of claim **1**, further comprising the step of using water as said working material.

10. The method of claim **1**, wherein said conduit comprises an inner conduit and wherein the method further comprises, prior to step (a), the steps of:

forming said heat exchanger using an outer conduit extending coaxially about said inner conduit so as to define a space between said inner and outer conduits, and

flowing said cryogenic fluid through said space to thereby remove heat from said inner conduit.

11. The method of claim **1**, further comprising the step of circulating at least a portion of said cryogenic fluid from a reservoir, through a pump, through said heat exchanger, through a condenser, and back to said reservoir.

12. The method of claim **11**, further comprising the step of circulating said cryogenic fluid through said pump and then through said heat exchanger.

* * * * *